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The materials investigations in this program have contributed to extending the wavelength range of high power diode lasers and to the development of improved OMVPE processes. The main research thrusts are OMVPE growth of wide bandgap alloys, and in-situ processes during OMVPE. Growth of large bandgap III-V phosphide alloys was developed for optoelectronic applications including red semiconductor lasers. The lattice matched materials system AlGaInP/GaAs resulted in high power, low threshold single quantum well lasers ($\lambda \approx 655$ nm). A materials investigation of a potentially shorter wavelength system, pseudomorphic GaInP/AlGaP-GaP, was initiated. Conventional growth was unsuccessful as the In containing alloys do not remain stable during high temperature growth of AlGaP. A multichamber OMVPE process employing flow modulation techniques was planned to overcome this problem. In-situ diagnostic techniques for OMVPE potentially offer real time measurements of growth rate and alloy composition. The feasibility to use Raman Spectroscopy during OMVPE was established by performing measurements on epitaxial III-Vs at high temperature (post growth). The phonon frequency shifts due to lattice expansion were measured and a temperature-tuned resonance was observed on GaAs at 600°C.

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I. Introduction

This program has focused on extending the range of III-V compound semiconductors materials which are useful in optoelectronic devices. To this end improvements in OMVPE processes were sought by establishing an in-situ diagnostic technique, and new III-V phosphide structures were grown by OMVPE. The first high power red laser source was demonstrated using AlGaInP heterostructures lattice matched to GaAs. Other visible materials systems for potentially shorter wavelength laser sources were identified and investigated. Raman Spectroscopy of epitaxial III-V compounds was investigated at high temperatures (up to 700°C). The relative temperature insensitivity of the observed spectra suggests this technique to be applicable as an in-situ probe. These investigations have contributed to the design of an improved OMVPE apparatus for new III-V materials and structures for use in optoelectronic devices.

IIA. Visible Laser Materials & Devices

Two materials systems were studied during this program, AlGaInP lattice matched to GaAs and AlGaP latticed matched to GaP with pseudomorphic GaInP direct bandgap regions. The former system has been extensively studied and characterized. Visible single quantum well GRIN-SCH laser diodes were fabricated and tested. The system on GaP was studied by first optimizing the growth of AlGaP alloys on GaP and then by attempting the growth of pseudomorphic GaInP/GaP structures. At moderate substrate temperatures ($\approx$ 750 °C) the In inter-diffused throughout the structure preventing quantum well fabrication.

Pulsed, room temperature operation of an AlGaInP graded-index separate confinement heterostructure laser grown by OMVPE was achieved. The laser active region consisted of a single 100 Å $Ga_{0.5}In_{0.5}P$ quantum well and 1600 Å graded index regions on both sides of the well. The graded index regions were produced by lattice-matched graded composition $(Al_yGa_{1-y})_{0.5}In_{0.5}P$ quaternary alloys. This structure reduces the broad-area threshold current compared to a double heterostructure laser, with pulsed thresholds as low as 1050 A/cm^2. Total pulsed power of 1.4 W at 658 nm was measured from an 80 μm$\times$300 μm mesa-stripe laser. Differential quantum efficiencies as high as

≈ 56% was measured. By examining the cavity length dependence of the threshold current density and quantum efficiency, it is apparent that the quantum well gain has not saturated in these structures. This suggests that devices containing a thinner single quantum well active region may result in a further reduction in threshold current density for visible lasers. These devices produce comparable powers as their AlGaAs counterparts making them attractive as visible diode pump sources for solid state laser systems.

Films of $Al_xGa_{1-x}P$ were grown with composition $x \leq 0.8$ on GaP substrates. The electronic and vibrational properties of the alloys were investigated using electrolyte electroreflectance and Raman spectroscopy, respectively. The compositional dependence of the phonon frequencies and electronic transition energies E_0 and E_1 were evaluated from the measured spectra. There are significant discrepancies between the vibrational frequencies obtained in this experiment and the previous literature. However, the dependence of E_0 and E_1 on composition is in good agreement with a previous experiment ($x \leq 0.58$). However, because of the greater composition range investigated, accurate evaluations of the nonlinear composition dependence (bowing parameter) for these two transitions were obtained. Lower growth temperature processes are required for this alloy in order to pursue the pseudomorphic visible laser system on GaP.

IIB. OMVPE In-Situ Raman Probe

The properties of several III-V compound semiconductor alloys, namely, GaAs, AlGaAs, and GaInP, have been studied at high temperatures using Raman spectroscopy. The temperature range used for these measurements includes the thermal dissociation temperatures for GaAs and GaInP in vacuum. The Raman spectra taken from the thermally dissociated surface yield information on the crystallinity (or lack of it) after decomposition in vacuum occurs. The phonon frequency shifts were determined with temperature, and found that the linewidth broadening of the Raman peaks at high temperatures (700°C) is minimal. These data establish the feasibility to acquire Raman spectra of these materials and deduce their alloy composition and layer thickness during epitaxial growth.

III. Publications, Presentations, Patents & Graduate Students

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Graduate Students - SDIO

B. Pitts

S. O'Brien